RHIC Collider Projections (FY2005 – FY2008)

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This note discusses in Part I possible operating modes for the RHIC Run-5 (FY2005) operating period including constraints from cryogenic cool-down, machine set-up and beam commissioning. In Part II a 4-year projection is given for gold-gold and polarized proton collisions, assuming that these modes are used in every run. This latest update is based on the experience gained during the Run-4 gold-gold and polarized proton operation.

Part I – Run-5 Projections

Cryogenic operation – After the summer shutdown the two RHIC rings will be at room temperature. They will be first brought to liquid nitrogen temperature, in about 30 days. Then, two weeks will be required to cool down to 4 Kelvin. At the end of the run, one week of refrigerator operation is required for the controlled warm-up to room temperature.

Running modes – A number of running modes are considered in RHIC, such as Si^{14+}, Ni^{28+}, Cu^{29+}, Fe^{26+}, and polarized proton collision. When starting the run we plan for 2 weeks of machine set-up with the goal of establishing collisions, and a 2-week machine development period ("ramp-up") after which stable operation can be provided with integrated luminosities that are a fraction of the maximum goals shown below. During the ramp-up period detector set-up can occur, however with priority for machine development. Estimates for set-up and ramp-up times are based on past performance, and improvements are likely in the future.

Higher weekly luminosities, and polarization, can be achieved with a continuous development effort in the following weeks. We propose to use the day shifts from Monday to Friday for this effort, with enough personnel available in the following shift to ensure production during the evening and night shift. The luminosity or polarization development efforts should stop when insurmountable limits, posed by the current machine configuration, are reached.

After a running mode has been established, a new mode can be set up in about 2 weeks (1 week set-up and 1 week ramp-up). This assumes that the injector has been set-up successfully to the required beam parameters during the preceding RHIC running mode. For the setup of polarized protons an extra week is needed for polarimeter set-up and polarization development. The collision energy in the same mode can be changed in 2-3 days, assuming that the energy is lowered and no unusual machine downtime is encountered.

For example, the FY2005 presidential request of 31 weeks of RHIC refrigerator operation could be scheduled in the following way, assuming that light or medium heavy ions are collided first, followed by polarized protons:

Cool-down from 80K to 4K	2 weeks
Set-up mode 1 (light or medium heavy ions)	2 weeks
Ramp-up mode 1	2 weeks
Data taking mode 1 with further ramp-up	10 weeks
Set-up mode 2 (polarized protons)	2 weeks
Ramp-up mode 2	1 weeks
Data taking mode 2 with further ramp-up	11 weeks
Warm-up	1 week

Past performance – Table 1 shows the Au-Au and p-p luminosities achieved in Run-4 (FY2004), and the d-Au luminosities achieved in Run-3 (FY2003). The time in store was 53%, 41%, and 32% of the total time for Au-Au (Run-4), p-p (Run-3), and d-Au (Run-3) respectively. The polarized proton Run-4 was for development only and therefore did not give a meaningful value for the time at store. Note that the total time includes all interruptions such as maintenance and beam studies.

Table 1: Achieved beam parameters and luminosities for Au-Au (Run-4), p-p (Run-4) and d-Au (Run-3).

Mode	# bunches	Ions/bunch $[10^9]$	β* [m]	Emittance [μm]	$\mathcal{L}_{peak}$ $[cm^{-2}s^{-1}]$	$\mathcal{L}_{store\ ave}$ $[cm^{-2}s^{-1}]$	L_{week}
Au-Au	45	1.1	1	15-40	15×10^{26}	4×10^{26}	160 μb^{-1}
p↑-p↑ *	56	70	1	20	6×10^{30}	4×10^{30}	0.9 pb^{-1}
d-Au	55	110d / 0.7Au	2	15	7×10^{28}	2×10^{28}	4.5 nb^{-1}

* Blue ring polarization of 45%, Yellow ring polarization of 40% in RHIC stores at 100GeV.

Luminosity projections – Table 2 lists the expected maximum peak and average luminosities for possible modes in Run-5 that could likely be achieved after a sufficiently long running period, typically several weeks, unless thus far unknown machine limitations are encountered. With experience from past runs we expect luminosities at the end of the initial ramp-up period to be lower than at the end of the running period by about a factor 4. For all modes it was assumed that the beam energy is 100 GeV/u. The average store luminosity is predictable from the beam parameters. The weekly integrated luminosity is then obtained using the ratio of the time in store to the total calendar time achieved in Run-4. The expected diamond rms length is 20 cm due to the availability of the full voltage from the 200 MHz storage cavities. No improvement is projected for Au-Au since the PHOBOS vacuum system, which was the main luminosity limitation in Run-4, is not upgraded.

Note that the quoted luminosities are for β* = 1 m. This is *only* available at PHENIX and STAR. PHOBOS and BRAHMS are limited to β* ≥ 3 m due to the lack of nonlinear IR correctors. Due to the required abort gaps in both beams, the maximum number of collisions can only be provided for two opposing IPs. The other IPs will have a 10% reduction in the number of collisions.

To minimize the time from store to store, stores of pre-determined length are desirable. They allow for a synchronized check of the injector chain before the store end. In Run-4 the store length was determined from the luminosity lifetime, the average time between stores, and additional considerations from the experiments.

Table 2: Maximum luminosities that can be reached after a sufficiently long running period.

Mode	# bunches	Ions/bunch [10^9]	β* [m]	Emittance [μm]	$\mathcal{L}_{peak}$ [$cm^{-2}s^{-1}$]	$\mathcal{L}_{store\ ave}$ [$cm^{-2}s^{-1}$]	L_{week}
Au-Au	45	1.1	1	15-40	15×10^{26}	4×10^{26}	160 μb^{-1}
Si-Si	28	14	1	20-35	8×10^{28}	3×10^{28}	6.5 nb^{-1}
Cu-Cu	28	7	1	20-35	3×10^{28}	1×10^{28}	2.5 nb^{-1}
p↑-p↑ (I)*	79	100	1	20-30	16×10^{30}	9×10^{30}	3 pb^{-1}
p↑-p↑ (II)*	56	150	1	20-30	25×10^{30}	15×10^{30}	4.5 pb^{-1}

*Polarized proton mode (I) assumes that only the warm snake is available in the AGS, and 45% polarization can be reached in RHIC stores. 4 experiments can be served. However, PHOBOS may be unable to run due to electron cloud induced pressure rises in the experiment. Mode (II) assumes that the AGS cold snake has been commissioned successfully, resulting in 50-60% polarization in RHIC stores. Only 2 experiments can be served.

Time dependence of integrated luminosity – Since we expect weeks of continuous ramp-up to reach the maximum weekly luminosities, the total integrated luminosities will be strongly time dependent. This is illustrated in Figure 1, which show as an example the projected Si-Si luminosities for a 14 weeks long physics run. For the projected maximum it is assumed that the weekly luminosity in Table 2 is reached after 8 weeks of linear ramp-up, starting with 25% of the final value. For the projected minimum it is assumed that the same charge per bunch can be accelerated and stored as has been reliably demonstrated for Au (see Table 1).

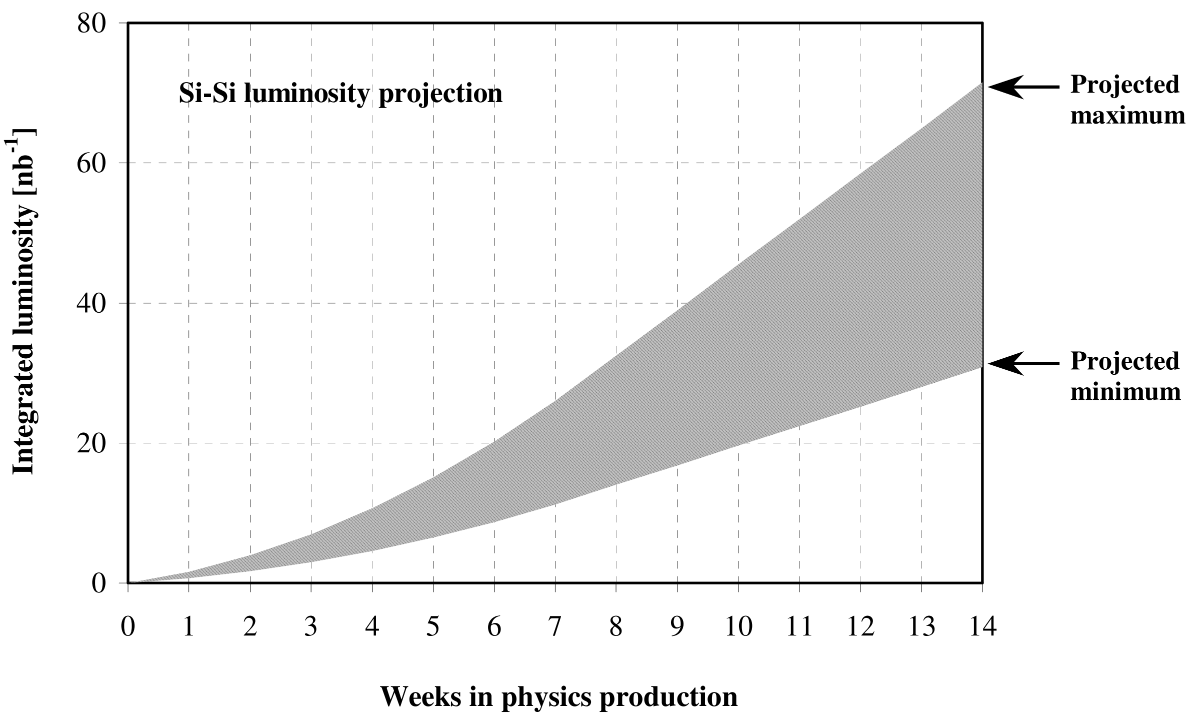

Figure 1: Projected minimum and maximum integrated luminosities for Si-Si collisions, assuming linear weekly luminosity ramp-up in 8 weeks.

Energy scans – It is preferable to lower the energy when the collision energy is changed in any given mode. This can be done in about 2-3 day. For more comments on luminosity scaling and restrictions for certain energies, see below.

Following are specific comments on the running modes:

Light or medium heavy ions – Since no vacuum upgrade of PHOBOS will be done for the next run, we expect pressure rises at PHOBOS to be the main luminosity limitation in ion operation. More than 100m of NEG coated beam pipes will be installed during the summer shutdown. However, the full benefit of these installations can only be realized after a PHOBOS vacuum upgrade. Vacuum upgrades are also planned for BRAHMS and STAR, which should reduce the backgrounds at these experiments. Efforts are under way to further increase the reliability of corrector power supplies, and reduce the number Quench Link Interlocks. A number of software projects will increase the operational efficiency.
For light or medium heavy ions, bunches with 10^{11} or more charges can be prepared. The listings for Si-Si and Cu-Cu serve as examples of intermediate heavy ions. The set-up for these species should not be more complicated than for d-Au operation in Run-3. Machine limitations from dynamic pressure rises should be encountered with approximately the same charge per bunch as with Au, unless the vacuum system is upgraded. Intra-beam scattering effects are reduced for particles with fewer charges. As a minimum, the same number of charges as in Run-4 Au-Au operation can be collided. For the maximum luminosities in Table 2, 1.7×10^{11} charges per bunch and 28 bunches were assumed. In this configuration, no vacuum problems were encountered with protons in Run-4, without the storage rf system. Note that with 4 collisions the total beam-beam tune spread is 0.012, i.e. RHIC would operate close to the beam-beam limit with ions. With lighter ions it may be possible to reduce β^* at STAR and PHENIX to 80cm. As an example, Figure 1 shows the minimum and maximum integrated luminosities for Si for a 14 weeks long physics run.

Polarized protons – We are proposing that a possible RHIC p-p run is scheduled later during the RHIC run so that a 4 week AGS polarized proton commissioning run can be completed before a RHIC p-p run would start. This would also allow finishing the installation of the AGS cold snake. Without the AGS cold snake, 50% polarization at AGS extraction, and 45% polarization in RHIC stores can be expected with bunch intensities of up to 10^{11} protons (scenario I in Table 2). After a successful initial commissioning of the AGS cold snake, the polarization could be raised to 50-60% even with higher bunch intensities (scenario II in Table 2). We expect at least 25% average polarization in store after 2 weeks of set-up, and 1 week of ramp-up. This should be improved to the values demonstrated in Run-4 (see Table 1) within a week. At higher luminosities PHOBOS may not be able to operate since the experiment's vacuum system will not be upgraded during the next shut-down. Figure 2 shows the projected minimum and maximum luminosity for scenario I (see Table 2).

Currently, our expectation for the completion of the AGS cold snake milestones are:

- 10/01/04 AGS infrastructure finished
- 10/15/04 magnet construction finished
- 12/15/04 magnet tests and measurements finished

The cold snake can be installed in the AGS in 4 maintenance days, or 3 consecutive days. A significant amount of commissioning time is needed before the cold snake can be used in operation. This set-up needs to be in parallel to the ion program, and also in parallel to the AGS polarized proton set-up without the cold snake. The AGS cold snake may become usable for operations towards the end of the polarized proton run.
For development the polarized jet target will be outside the ring during the ion run, and needs to be installed before the polarized proton run starts. A 3-day access period for its installation is included in the 2-week start-up period. The vacuum performance of the jet target is expected to be improved in Run-5. Its vacuum performance may, however, still limit the luminosity and the jet may need to be removed to maximize the luminosity.

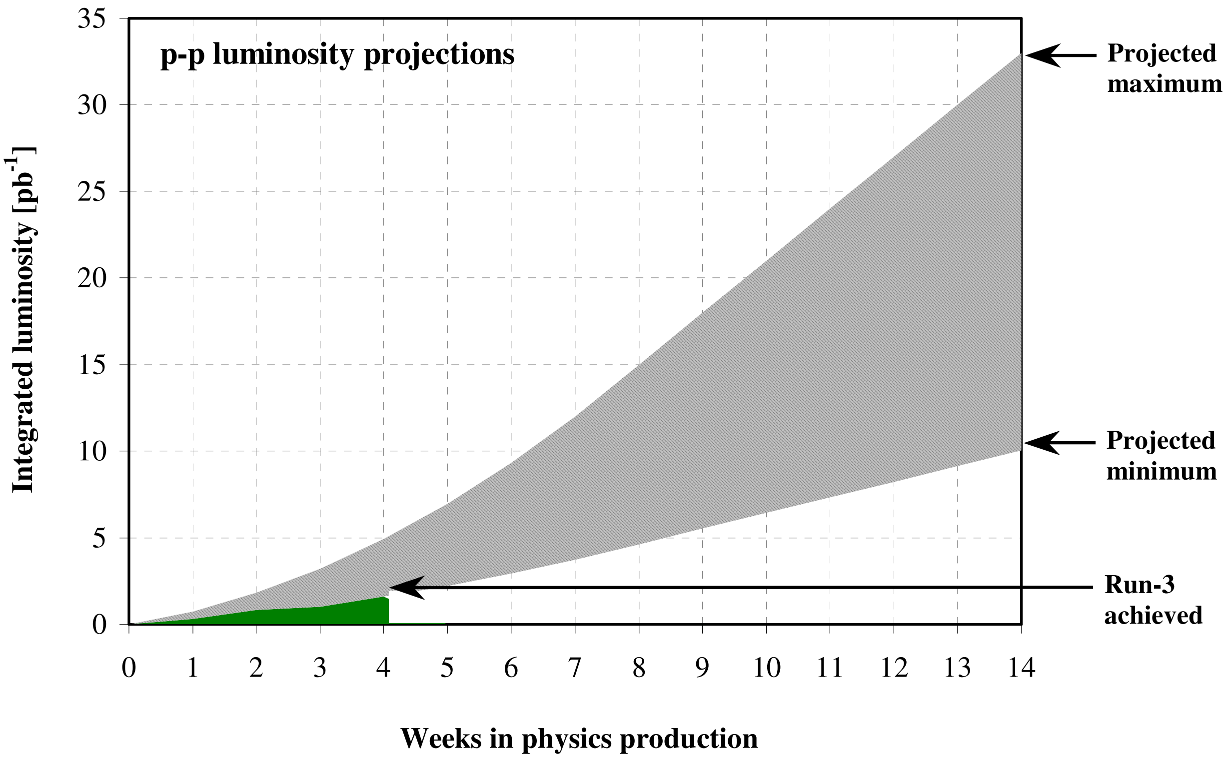

Figure 2: Projected minimum and maximum integrated luminosities for polarized proton collisions, assuming linear weekly luminosity ramp-up in 8 weeks, and availability of the AGS warm snake only. 45% polarization is expected in RHIC stores.

Part II – 4-Year Projections

In both Au-Au and p-p operation RHIC exceeds the design luminosity. The 4-year plan laid out below aims at reaching the “enhanced” RHIC luminosity consisting of

$\mathcal{L}_{\text{store ave}} =$ **8×10^{26} cm^{-2}s^{-1} for Au-Au at 100 GeV/u (4× design)**

$\mathcal{L}_{\text{store ave}} =$ **6×10^{31} cm^{-2}s^{-1} for p-p at 100 GeV,**
$\mathcal{L}_{\text{store ave}} =$ **1.5×10^{32} cm^{-2}s^{-1} for p-p at 250 GeV (16x design)**
both with 70% polarization

Below we present 4-year luminosity projections for gold-gold collisions and polarized proton collisions. Should a major repair be necessary during a run, leading to weeks of downtime, the projections do not hold. Projections over several years are not very reliable and should only be seen as guidance for the average annual machine improvements needed to reach the enhanced luminosity goals.
We assume for one mode a set-up time of 4 weeks, and for the other mode of 3 weeks. For both modes we assume a luminosity production period of 12 weeks in each fiscal year from 2005 to 2008. Note that running 4+12 weeks of Au-Au, and 3+12 weeks of p-p in a single year requires 34 weeks of cryo-operation.
The weekly luminosity starts at 25% of the final value, and increases linearly in time to the final value in 8 weeks. During the remaining weeks the weekly luminosity is assumed to be constant at the values listed in Table 4 and Table 5. We take for the final minimum weekly luminosity a value that has been reliably demonstrated in the past. The yearly evolution of the final maximum weekly luminosity is based on the assumption that all the improvements outlined below are successful and that a minimum of 12 weeks of physics running in the particular mode is scheduled every year to allow for commissioning of the improvements and development of the machine performance. However, the most likely luminosity evolution is in between these two boundaries. Future updates will change these projections significantly, in particular the minimum projections. Should one of the modes not be run in any particular year, the performance development will be delayed.

Luminosity limitations – A number of effects limit the achievable luminosity. High intensity beams lead to a vacuum breakdown, caused by electron clouds and beam loss driven desorption. This problem may be cured through the installation of NEG coated beam pipes in the warm sections. Pressure rises in PHOBOS after rebucketing have limited the Au-Au luminosity in Run-4. Intrabeam scattering increases the transverse emittance during stores and causes debunching. Ultimately, electron cooling is required, beyond the 4-year outlook of this note. The beam-beam interaction limits the beam and luminosity lifetime especially for protons. Furthermore, in proton operation only 2 collisions per turn can be accommodated with high bunch intensities. Instabilities, especially around transition will require a transverse damper in the future. Table 3 lists the main projects to address these and other issues. Some of the listed projects may shift in time or extend further into the future. In addition, new projects will appear, as we better understand the machine limitations.

Operation at energies other than 100 GeV/u – For Au-Au operation at 100 GeV/u with $\beta^* = 1$ m the limiting aperture is in the triplet. For energies less than 100 GeV/u the unnormalized beam emittance is larger and, to maintain the beam size within the triplet, the β-function in the triplet has to be reduced, which results in a larger β^*. The combined effect is that the luminosity scales with the square of the energy, i.e. at 10 GeV/u β^* is 10 m and the luminosity is reduced by 100 from its value at 100 GeV/u. This is shown in Figure 3. For BRAHMS and PHOBOS the scaling is slightly modified, since it is favorable to cross the transition energy, corresponding to the relativistic $\gamma = 23$, with $\beta^* = 5$m in all IPs, and not to un-squeeze β^* after transition crossing. Note that operation near the transition energy is not possible, and that the storage rf system cannot be used below the transition energy.

For p-p operation the luminosity is expected to increase linearly with energies above 100 GeV. Initial operation at 250 GeV requires about 6 weeks of commissioning time for both luminosity and polarization development.

Time in store – The fraction of the time in stores divided by the total time, reached 53% for gold-gold collisions and 41% for polarized proton collisions in Run-3. This can still be improved in a number of areas (see Table 3). Time can be gained through faster machine set-up, the reduction of magnet quenches, faster down ramps, and improved reliability of the corrector power supplies. In p-p operation, time can also be gained through the acceleration of multiple bunches in each AGS cycle. We project that the time in store can be increased to about 100 hours per week, or 60% of calendar time.

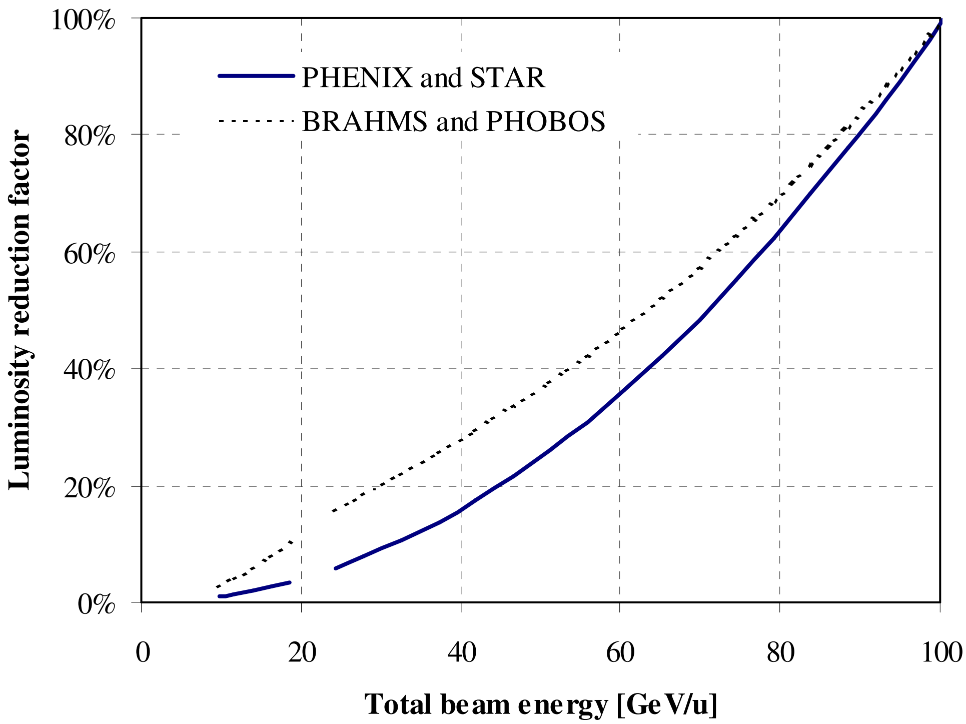

Figure 3: Luminosity scaling for Au-Au operation at energies below 100 GeV/u.

4-year projections – In Table 4 luminosities are estimated for gold-gold collisions, assuming 12 week of luminosity production. For the maximum luminosities quoted in this table, the projects listed in Table 3 need to be completed successfully. Figure 4 shows the total integrated luminosities for the period under consideration.

In Table 5 and Figure 5 the projection for polarized proton collisions are displayed. Table 5 also shows the expected evolution of proton beam polarization for operation at 100 GeV. The main improvements come from increased polarization in the AGS due to the installation of a super-conducting strong partial snake (2005) and a new super-conducting solenoid for the OPPIS source (2007). The benefits of a second super-conducting strong partial snake for the AGS (2007) are also being investigated.

Table 3: Main improvement projects for the RHIC injectors, luminosity and background, and time in store.

For FY2005	For FY2006	For FY2007	For FY2008
	RHIC injectors		
AGS cold helical snake		New OPPIS solenoid	EBIS test
	RHIC luminosity and background		
Collimation system, vertical	Transverse damper system		
Vacuum upgrade BRAHMS	Vacuum upgrade PHOBOS		
Vacuum upgrade STAR	Vacuum upgrade PHENIX		
NEG pipes (200 m)	NEG pipes (300 m)		
	Solenoids?		
Stochastic cooling test	Stochastic cooling test	Stochastic cooling	
	RHIC time in store		
FEC PS replacement	FEC PS replacement	FEC PS replacement	
QLI reduction	QLI reduction	QLI reduction	
All BPM electronics to alcoves	BPM system upgrade	Injection set-up	
BPM system upgrade	Injection set-up		
Gradient error correction	Decoupling (ramp)		
Tune feed-forward (ramp)			
Decoupling (ramp and store)			
Corrector PS reliability			
Faster down-ramps			
Injection set-up			
Unroll one triplet, vibration test			

Table 4: Projected RHIC Au-Au luminosities.

Fiscal year		2002A	2004A	2005E	2006E	2007E	2008E
No of bunches	…	55	45	45	78	88	112
Ions/bunch, initial	10^9	0.6	1.1	1.1	1.1	1.1	1.1
Average beam current/ring	mA	33	49	49	85	96	122
$\beta*$	m	1	1	1	1	1	1
Peak luminosity	10^{26} cm^{-2}s^{-1}	5	15	15	25	28	36
Average store luminosity	10^{26} cm^{-2}s^{-1}	1.5	4.0	4.7	6.3	7.1	9.0
Time in store	%	25	53	56	58	59	60
Maximum luminosity/week	μb^{-1}	25	160	159	220	253	327
Minimum luminosity/week	μb^{-1}			160	160	160	160
Maximum integrated luminosity	μb^{-1}	89	1370	1430	1980	2280	2940
Minimum integrated luminosity	μb^{-1}			1440	1440	1440	1440

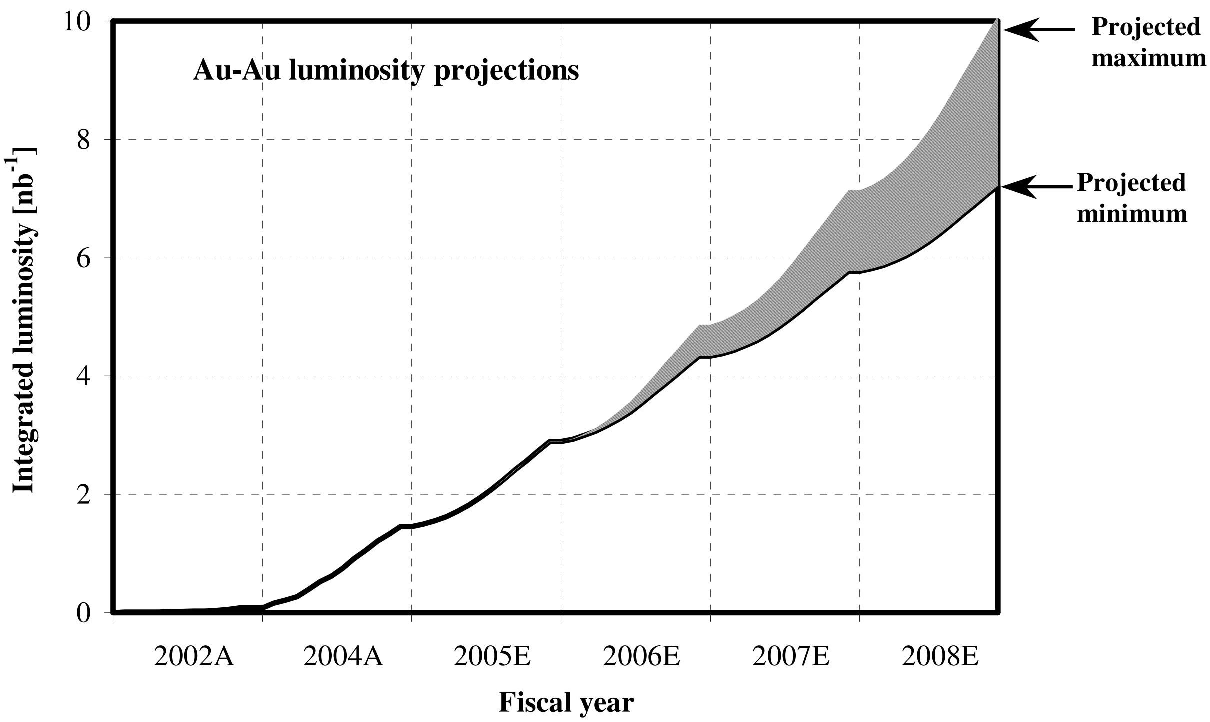

Figure 4: Minimum and maximum projected integrated luminosity for Au-Au collisions.

Table 5: Projected RHIC p-p luminosities and polarization.

Fiscal year		2002A	2003A	2004A	2005E	2006E	2007E	2008E
No of bunches	…	55	55	56	79	79	100	112
Ions/bunch, initial	10^{11}	0.7	0.7	0.7	1.0	1.4	2.0	2.0
Average beam current/ring	mA	48	48	52	99	138	250	280
β*	m	3	1	1	1	1	1	1
Peak luminosity	10^{30} cm^{-2}s^{-1}	2	6	6	16	31	80	89
Average store luminosity	10^{30} cm^{-2}s^{-1}	1.5	3	4	9	22	64	72
Time in store	…	30	41	38	50	53	56	60
Maximum luminosity/week	pb^{-1}	0.2	0.6	0.9	2.8	7.1	21.6	26.0
Minimum luminosity/week	pb^{-1}				0.9	0.9	0.9	0.9
Maximum integrated luminosity	pb^{-1}	0.5	1.6	3	25	64	195	234
Minimum integrated luminosity	pb^{-1}				8	8	8	8
AGS polarization at extraction	%	35	45	50	60	75	80	80
RHIC store polarization, average	%	15	30	40	45	65	70	70
Maximum LP^4/week	nb^{-1}	0	5	24	120	1260	5190	6230
Minimum LP^4/week	nb^{-1}				24	24	24	24

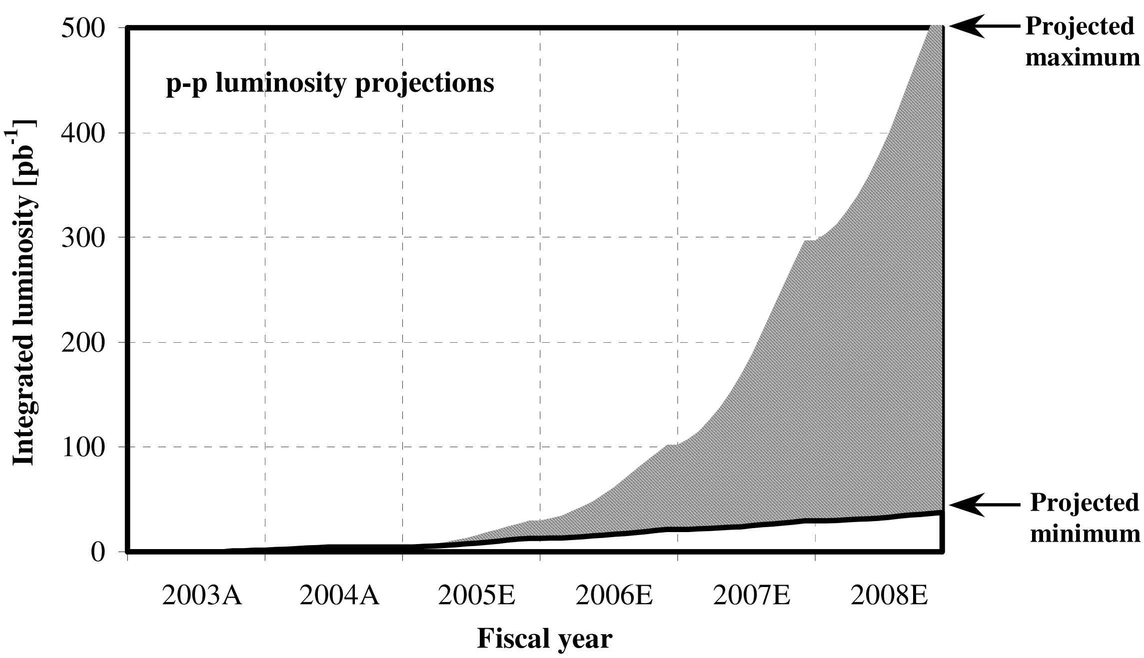

Figure 5: Minimum and maximum projected integrated luminosity for p-p collisions.